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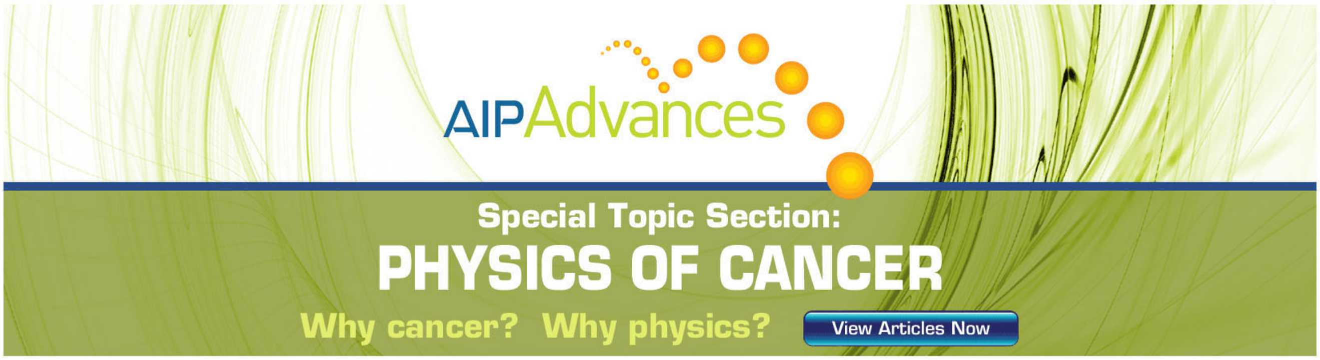

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JOURNAL OF APPLIED PHYSICS **111**, 07E325 (2012)

# Extended frequency analysis of magnetic losses under rotating induction in soft magnetic composites

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We present novel results on magnetic losses in soft magnetic composites (SMCs) excited with rotating field. Soft composites are very promising in electrical engineering applications, where new topologies of electrical machines with two- and three-dimensional induction loci are increasingly found. An experimental characterization of industrial SMC products has, therefore, been carried out, up to the kilohertz range, under alternating and circular flux loci, making use of a specifically designed and optimized loss measuring setup. The obtained results have been analyzed for all kinds of excitation, according to the loss separation concept, with the emphasis being placed on the relationship between the rotational and the alternating loss components. In particular, it is found that the ratio between the rotational and the alternating losses is, for any given peak induction, independent of frequency. © *2012 American Institute of Physics*. [doi:10.1063/1.3675177]

## I. INTRODUCTION

Nowadays, machine designers are working on new machine topologies such as hybrid excitation motors.[1] Since three-dimensional (3-D) flux paths are encountered in such machines, a clear advantage is expected from the use of isotropic soft magnets. Contrary to laminated materials, soft magnetic composites (SMCs) fulfill 3-D isotropy requirements[2] and, due to their granular structure, they exhibit reduced eddy currents, making them suitable for high speed electrical machines.[3] However, the measurement and analysis of the magnetic loss under 2-D and 3-D flux loci in SMCs are challenging topics,[4,5] In a typical 2-D testing configuration, developed for magnetic sheets, a square sample is placed at the center of a laminated horizontal/vertical double yoke,[6,7] however, poor homogeneity of the magnetic induction may occur in the measuring region. The situation can be improved by adopting a circular/hexagonal sample excited by a three-phase magnetizer.[8,9] However, whatever method is used, the maximum exciting frequency reported in the literature does not exceed 200 Hz. This is sufficient for soft magnetic laminations,[10] however, given their prospective high-frequency applications, it is not suitable for SMCs. In any case, the problem of assessing the experimental results against physical modeling arises,[4] which, in analogy with the approach followed in the analysis of 2-D energy losses in magnetic laminations, can rely on the concept of loss separation. Actually, the statistical theory of losses (STL) is fully demonstrated for one-dimensional magnetization processes only,[11] however, it is also shown phenomenologically to apply in magnetic sheets for 2-D magnetization paths.[10] We can, in this case, after having isolated the hysteresis loss component, $W_{\mathrm{hyst}}{}^{(\mathrm{circ})}$, and calculated the rotational classical losses, $W_{\mathrm{class}}{}^{(\mathrm{circ})} = 2\ W_{\mathrm{class}}{}^{(\mathrm{alt})}$, bring to light the excess dynamic losses and their dependence on frequency. Remarkably, it is obtained that the ratio, $R_{\mathrm{exc}}(B_{\mathrm{P}}) = W_{\mathrm{exc}}{}^{(\mathrm{circ})}(B_{\mathrm{P}})/W_{\mathrm{exc}}{}^{(\mathrm{alt})}(B_{\mathrm{P}})$, of the rotational to alternating excess losses is independent of the frequency.

In this paper, we present an investigation on the 2-D energy losses in SMCs, focusing our attention on the following points: 1) Experimental characterization under circular induction of commercial SMCs, up to 4 kHz. An optimally designed apparatus is used on purpose. 2) Analysis of the experimental results in the framework of the SLT and the ensuing loss separation procedure, with the identification of the loss components versus the peak induction, $B_{\mathrm{P}}$, and magnetizing frequency, $f$. In analogy with the behavior of soft magnetic laminations,[10] a frequency-independent excess loss ratio, $R_{\mathrm{exc}}(B_{\mathrm{P}})$, is found.

## II. EXPERIMENTAL PROCEDURES

In order to achieve the best homogeneity of the sample induction, a three-phase magnetizer has been employed, by which testing under alternating, and rotational fluxes can be made. The topology and dimensions of the three-phase excitation system, which is schematically shown in Fig. 1, have been optimized through a design procedure based on a finite element method. The disk-shaped samples (diameter, 80 mm; thickness, 3 mm), cut from an SMC cylinder produced by Höganäs,[12] are placed in a precise manner inside the magnetizer bore, with a 1 mm air-gap left between the sample and bore wall. Double $B$-coils and $H$-coils, centered over a 40 mm × 40 mm sample area, have been used for the induction and field acquisition, with the desired induction loci being attained by digital feedback implementing the contraction mapping principle.[9] The measurements have been performed

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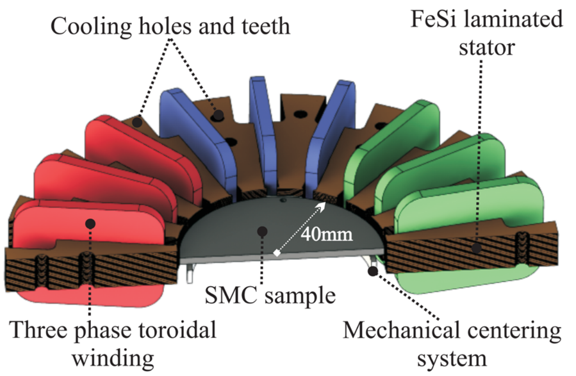

FIG. 1. (Color online) The employed three-phase magnetizer and the disk-shaped 80 mm diameter SMC test sample.

up to $f = 4$ kHz under alternating and 2-D flux at $B_P$ levels ranging between 0.25 and 1.25 T. The alternating loss is obtained by applying the field along two orthogonal directions and averaging the results. It is noted, however, that the two results are nearly coincident, confirming the isotropic properties of these materials. Although one phase of the magnetizer would be, in principle, sufficient to create the alternating field, the three phases are used to change the magnetizing direction without being obliged to manually rotate the sample. For the circular case, the averaging is made from the loss figures found upon clockwise and counterclockwise rotation. The so-obtained measurements are summarized in Fig. 2.

## III. LOSS SEPARATION

### A. Loss separation under alternating sinusoidal induction

The losses measured under alternating sinusoidal induction have been analyzed following the same procedure outlined in Ref. 13. Accordingly, the classical loss component, $W_{class}^{(alt)}(B_P, f)$, is calculated under the assumption that eddy currents are confined in the grains, whose size and shape distributions are known from micrographic investigation. The value of the hysteresis loss, $W_{hyst}^{(alt)}(B_P)$, is obtained by extrapolating, to zero frequency, the quantity,

$$W_{diff}^{(alt)} = W^{(alt)} - W_{class}^{(alt)} = W_{hyst}^{(alt)} + W_{exc}^{(alt)}, \quad [\mathrm{J/m^3}], \tag{1}$$

where $W^{(alt)} = W^{(alt)}(B_P, f)$ is the measured loss and $W_{exc}^{(alt)} = W_{exc}^{(alt)}(B_P, f)$ is the excess component. It has been shown in Ref. 13 that the STL provides, for $W_{exc}^{(alt)}$, the expression,

$$W_{exc}^{(alt)}(B_P, f) = 2 n_o V_o \left( \sqrt{1 + \frac{16 \sigma_{Fe} G S V_o}{(n_o V_o)^2} B_P f} - 1 \right), \ [\mathrm{J/m^3}], \tag{2}$$

which is exploited to fit $W_{diff}^{(alt)}$. In this equation, $\sigma_{Fe}$ is the iron conductivity, $G = 0.1356$, $S$ is the sample cross section, and the parameters $n_o$ and $V_o$, which depend on $B_P$, lump the effect of the material microstructure. The fitting procedure permits one to obtain the behavior of the parameters, $n_o$ and $V_o$, versus $B_P$. It is noticed that, at sufficiently high frequencies, $W_{exc}^{(alt)} \propto f^{1/2}$.[9]

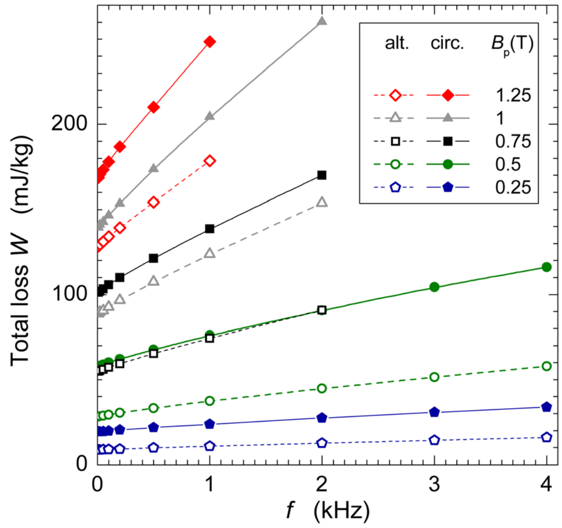

FIG. 2. (Color online) Energy loss per cycle measured in SMCs under alternating sinusoidal induction and circular induction as a function of frequency at different $B_P$ values.

### B. Loss separation under rotating induction

The loss separation procedure is straightforwardly applied when the induction is circular. Since the two orthogonal induction components are also in quadrature in the time domain, we obtain $W_{class}^{(circ)}(B_P, f) = 2 \cdot W_{class}^{(alt)}(B_P, f)$ (Parseval theorem). The excess loss under the rotating induction is defined as,

$$W_{exc}^{(circ)}(B_P, f) = W_{tot}^{(circ)}(B_P, f) - \left( W_{hyst}^{(circ)}(B_P) + W_{class}^{(circ)}(B_P, f) \right), \tag{3}$$

where the rotational hysteresis loss, $W_{hyst}^{(circ)}(B_P)$, is given by the extrapolation of the total loss, $W^{(circ)}(B_P, f)$, to zero frequency. However, the description of $W_{exc}^{(circ)}$ by an equation similar to Eq. (2) can only have a euristic value, because the magnetization process under rotating induction proceeds by mechanisms quite different from the ones operating under alternating induction, and the corresponding application of the SLT has not yet found a clear physical description.

In order to phenomenologically relate the alternating and 2-D magnetic losses, we introduce the ratios $R_{hyst}(B_P) = W_{hyst}^{(circ)}(B_P)/W_{hyst}^{(alt)}(B_P)$, $R_{class}(B_P, f) = W_{class}^{(circ)}(B_P, f)/W_{class}^{(alt)}(B_P, f) = 2$, and $R_{exc}(B_P, f) = W_{exc}^{(circ)}(B_P, f)/W_{exc}^{(alt)}(B_P, f)$. These quantities can be exploited to predict the loss figures under the elliptical regime, starting from a limited number of measurements under alternating and circular flux. Figures 3 and 4 provide the experimental circular-to-alternating loss ratios, $R_{hyst}$ and $R_{exc}$, versus the peak induction. The latter is taken at different frequencies, ranging between 20 Hz (which is quasi-static in these materials) and 4 kHz. Both $R_{hyst}$ and $R_{exc}$ are monotonically decreasing with $B_P$, thereby reproducing, to a good extent, the behavior exhibited by the same quantities in magnetic laminations,[10] but for a narrower range of $B_P$ values. This limitation is imposed by the much harder magnetic response of the composite materials. Remarkably, it is found that $R_{exc}$ behaves quite independently of the

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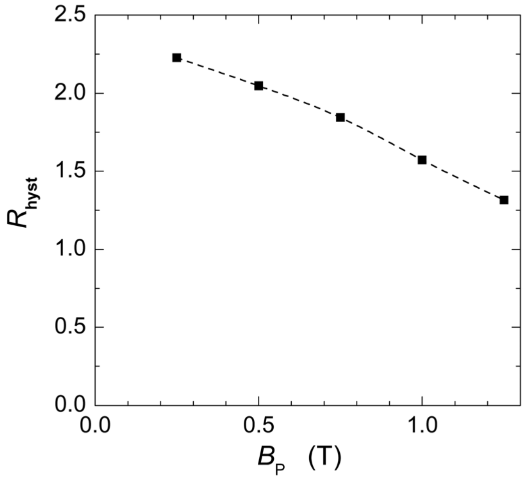

FIG. 3. Hysteresis loss ratio, $R_{hyst}(B_P) = W_{hyst}^{(circ)}(B_P)/W_{hyst}^{(alt)}(B_P)$, vs peak induction, $B_P$.

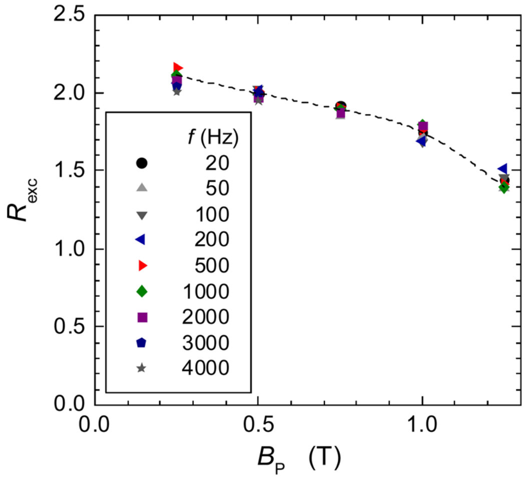

FIG. 4. (Color online) Excess loss ratio, $R_{exc}(B_P) = W_{exc}^{(circ)}(B_P, f)/W_{exc}^{(alt)}(B_P, f)$, vs peak induction, $B_P$. This quantity is found to be quite independent of frequency (from DC to $f = 4$ kHz).

frequency, again, similar to what is observed in soft laminations.[10] It is an important property, leading to a great simplification in the prediction of the loss under more complicated induction loci. For example, all the formalism developed in Ref. 14 for the prediction of the loss under elliptical induction loci can be applied for SMC.

## IV. CONCLUSIONS

In this paper, we have demonstrated the behavior of the magnetic losses in SMCs under alternating and circular induction in a broad frequency range. The experiments have been made possible up to 4 kHz by use of a specially developed three-phase magnetizer in association with a digital feedback system. The loss separation procedure has been carried out both under alternating and rotating conditions. A major result is obtained, where the ratio between the excess loss under circular and alternating induction is found to be independent of *f* in a wide frequency range. This brings about a significant simplification in the loss analysis of complex induction loci.

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